Chapter 15
Dredge Measurement and Payment Volume Computations

15-1. General Scope

A primary use of hydrographic surveys supporting river and harbor construction is to determine the quantity of material that is excavated or placed. These material quantity estimates are used for design/bidding purposes and contracted construction payment. This chapter deals with the computation of dredged quantities (either excavated or placed) as determined from in-place hydrographic surveys. Other methods of estimating dredged quantities (scow/bin load measurements, production flow rates, station/face cut dredging, etc.) are not covered. This chapter prescribes Corps-wide standards for performing dredge quantity computations.

15-2. Dredge Volume Computation Techniques--Background

Dredge volume computation procedures in the Corps have generally followed those used in railroad and roadway construction--the Average End Area (AEA) method. Cross-sections of a channel are taken at a constant interval and the quantity is computed based on the volume between the cross-sections. The major assumption is that the cross-sectional area is relatively constant between two successive cross-sections. If not, then this method becomes an approximation (or estimate) of the true volume. Decreasing cross-sectional spacing to improve the AEA computation accuracy had economic limits due to increased field survey costs. Thus, cross-sectional spacing for most dredging work ranged from 100- to 500-feet throughout the Corps. Alternate computational methods have been used to compute volumes of sparse cross-sectional data. These include the prismoidal correction to the AEA method and the Triangulated Irregular Network (TIN) method.

a. Since the 1970's, multiple-transducer sweep systems and multibeam systems have provided a dense, full bottom coverage of a channel, allowing for more accurate quantity take-offs than that using only sparse 100- to 500-ft sections. In effect, these full-coverage systems provide cross-sections at 1- to 5-foot spacing, or data densities ranging from 1 to 5 sq ft. Quantities can be computed using the AEA method at the denser sectional spacing, or using vertical projection methods of the individual elements.

b. In general, all commonly used volume computation methods reduce down to that of determining the area bounded by a finite group of data points and projecting this area over some length to obtain a prismoidal volume. These projections may be done either horizontally or vertically, as shown in Figure 15-1. The methods used in the Corps are:

- Average End Area -- used for sparse cross-section data
- Triangulated Irregular Network-- used for sparse cross-section data
- Bin -- used for dense multibeam coverage data

For most USACE construction and dredging work, the horizontally-projected average end area (AEA) method has been considered the standard volume computation method when sparse cross-section data is available (i.e, 100- to 500-ft spaced cross-sections). An alternate method is to develop vertical prismoidal elements between the sparse cross-sectional data, and compute the volume of each prismoidal element--a vertical projection. See Figure 15-1. Development of the triangular prisms between two cross-sections is termed a Triangulated Irregular Network, or "TIN." TINs have application when data are sparse, such as is typical in widely spaced cross-sections, and where cross-line data is available. When full-coverage data is available from multiple transducer or multibeam systems, it can be gridded or binned at a dense grid spacing, and volumes computed from the vertical projection of each grid cell to a reference surface.

c. In Figure 15-1, the AEA volume is a function of the horizontally projected areas of each cross-section--A_1 and A_2 -- projected along the distance (L) between the two sections. An approximate volume results from this AEA computation. When TIN prismoidal elements are generated for data points between the two cross-sections, the volume of each prismoidal element can be computed given the X-Y-Z coordinates of the three vertices--i.e., observed depths converted to elevation differences above (below) the reference channel surface/prism. The resultant volume computation is somewhat more accurate than the AEA method. If full-coverage binned data are available, then the volume of each grid cell can be computed given the cell area on the reference surface (A_b) and the elevation (h_b) of the depth above (or below) that reference surface. Given the higher-density coverage, this is the most accurate volume. AEA or TIN volume computation methods may also be used to compute quantities when densely gridded data is available; however, this adds an extra step to the process.

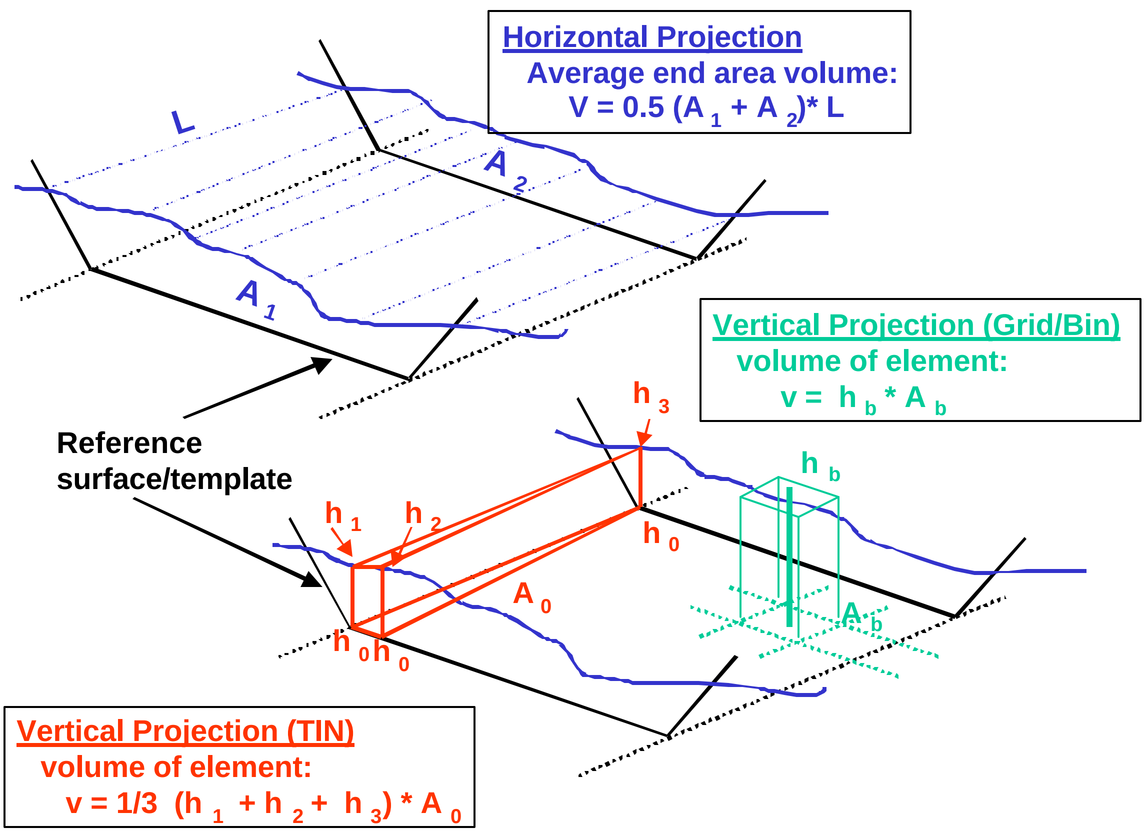


Figure 15-1. Generalized depiction of Average End Area, TIN, and binned volume computation methods

15-3. Average-End-Area Volume Computations

Traditionally, earthwork or dredging quantities for purposes of design estimates and construction payment have been obtained from cross-sectional surveys of the project area. These surveys are normally run perpendicular to the general project alignment at a predetermined constant spacing. The elevation data are plotted in section view along with the design/required depth and/or allowable overdepth templates. One or more reference or payment templates may be involved on a dredging project (e.g., zero tolerance, null ranges, etc.). Given sectional plots of both preconstruction and postconstruction (as-built) grades (or, in some cases, intermediate partial construction grades), the amount of excavated (cut) or placed (fill) area can be determined at each cross section. Figure 15-2 shows the typical templates used to compute relative cut/fill quantities. The sectional area can be determined by use of any number of manual or automated methods. The average areas of two successive cross-sections are computed, and these averages are then projected along the project alignment (linear or curved) by a distance equal to the sectional spacing, resulting in an approximate estimate of the volume of material cut or filled during construction. This approximate estimating technique is known as the trapezoidal or average-end-area method and is universally used (and accepted) in highway, railroad, and marine construction for design estimating and payment purposes.

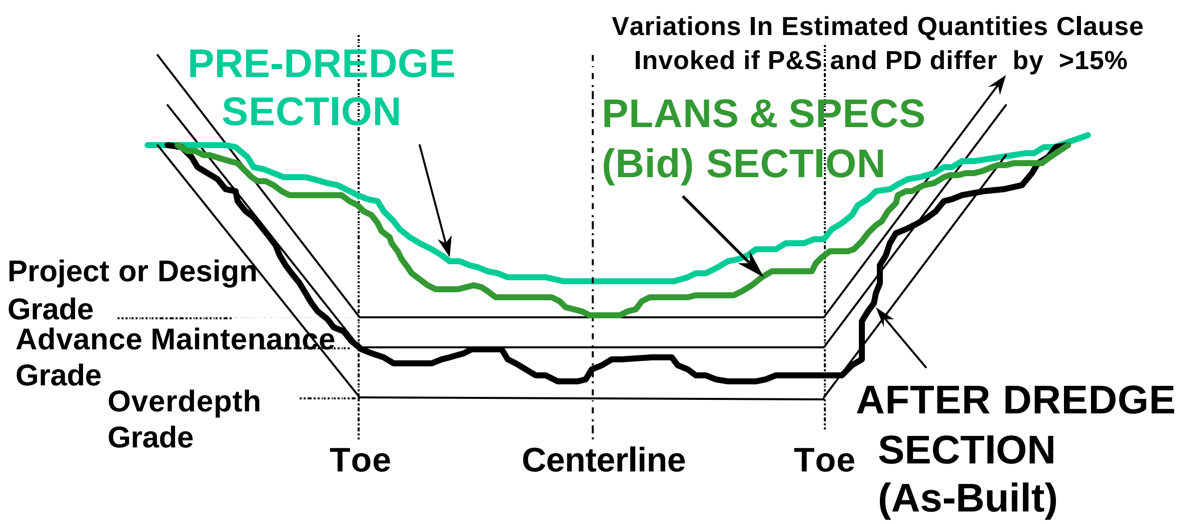


Figure 15-2. Typical reference templates from which payment quantities are computed using AEA methods

a. Average End Area computation formulas. Given two successive cross sections of areas A_1 and A_2 and distance L apart (Fig 15-1), the equation for an average end area volume between two cross sections is:

$$V = (L/2) \cdot (A_1 + A_2) \tag{Eq 15-1}$$

Cross-sectional areas are measured in square feet, and the resultant volume is converted to cubic yards by dividing the measure area by 27 cubic feet/cubic yard (*cf/cy*).

$$V = (L/54) \cdot (A_1 + A_2) \tag{Eq 15-2}$$

where A_1 and A_2 are expressed in square feet.

In cases in which even 100-ft cross sections are run, the formula simplifies to

$$V = (1.852) \cdot (A_1 + A_2) \tag{Eq 15-3}$$

The results of Equations 15-1 through 15-3 are exact *only* when the end areas are exactly equal (i.e., $A_1 = A_2$). As one end area approaches zero, the trapezoidal element becomes a pyramid, and the error in using the average-end-area volume formula approaches 50 percent. This commonly occurs in dredging projects where large area variations are found between successive cross-sections.

b. Prismoidal correction to AEA. Various types of prismoidal correction formulas have been developed over the years to compensate for this inherent inaccuracy in average-end-area volumes. More often, however, a higher accuracy is achieved by decreasing the cross-sectional spacing in attempts to define the terrain more precisely (e.g., cross-sectional areas become more nearly equal). This increased field survey densification increases costs, which may not be proportionate to the increase in accuracy obtained, primarily because, in this procedure, survey alignments are restricted to obtaining cross sections over rigid orientation alignments, and these rigid alignments may not be the most practical or efficient method of densifying ground coverage. In fact, for most typical marine construction dredging projects, obtaining cross sections of channels is often the least efficient survey alignment, due to many factors associated with the offshore survey process. When survey alignments are run parallel (i.e., longitudinal) to the project/channel alignment, cross-sections may be easily developed from the DTM (possibly a TIN) database. This is done by passing sectional spaced planes through the database and interpolating depths at the intersecting section planes. From these simulated cross sections, volumes can be computed by use of the average-end-area method. If prismoidal (or Simpson's) formulas or corrections are used in lieu of standard average-end-area methods, the construction specifications should identify that fact. Use of prismoidal corrections is rarely done in practice.

c. Box cut allowance. a limited number of districts provide an allowance for material left above the pay prism grade on side slopes when sufficient non-pay excavation has been performed at the base of the slope to allow for sloughing. Such box cut quantities must be computed separately due to limitations in payment which shall not exceed the excessive excavated yardage at the base of the slope. This allowance is illustrated in Figure 15-3. Box cut payment allowances are not uniformly applied throughout the Corps--e.g., payment for over-excavation inside the channel. Automated computation of box cut allowances adds significant complexity to the quantity take-off process. Often box cut quantities are negligible relative to the overall volume. For these, and other reasons, Corps-wide use of a box cut allowance is no longer recommended except in unique circumstances. The following contract clause is typical of those used for box cut allowances:

> 3.4.3 Side Slopes
>
> Side slopes may be formed by box cutting or dredging along the side slope. Material actually removed, within the limits approved by the Contracting Officer, to provide for final side slopes not flatter than shown on the contract drawings, but not in excess of the amount originally lying above this

limiting side slope, will be estimated and paid for in accordance with the provisions contained in paragraphs, "Measurement" and "Payment" above. Such amount will be estimated and paid for whether dredged in original position or by box cut dredging whereby a space is dredged below the allowable side slope plane on the bottom of the slope for upslope material capable of falling into the cut. End slopes and transition slopes will not be estimated and paid for under this contract. In such cases, a 0 horizontal on 1 vertical will be used with no upslope allowance provision applied outside the required prism.

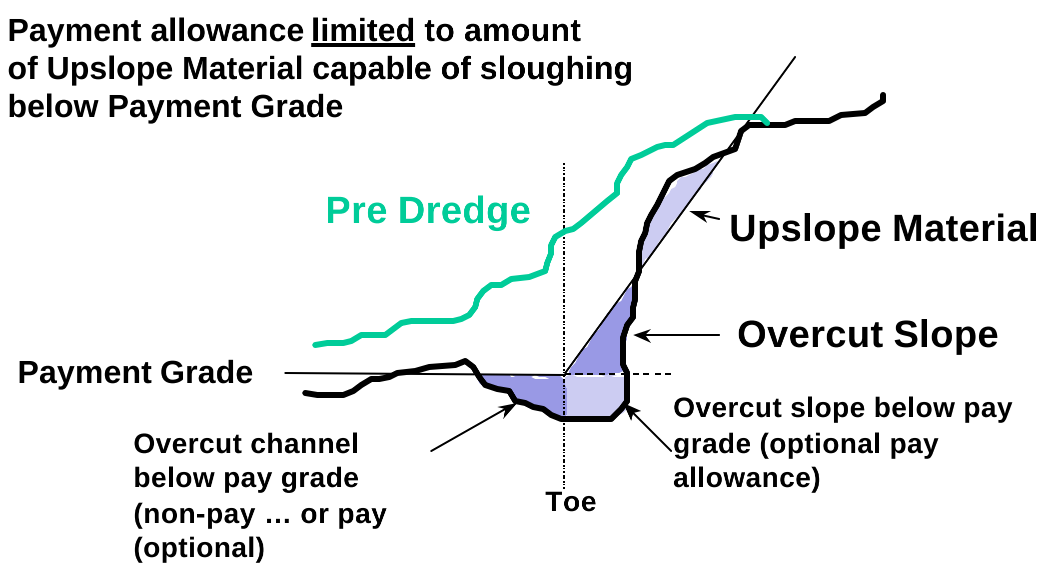


Figure 15-3. Box cut payment allowance

d. Cross-sectional area computations. Over the years, Corps districts have used a number of methods to compute the area of a cross-section that is used in the AEA volume computation. Some of the more prevalent methods of computing cross-sectional areas for dredging are listed below. Details on most of these methods can be obtained in any engineering/surveying handbook.

(1) Direct formula. Various formulas have been developed for computing areas directly from cross-section notes. All generally presume that a slope stake elevation (i.e., grade-side slope intercept point) has been determined along with uniform spacings off the centerline of the channel. Thus, these methods are not useful for dredging work.

(2) Area by coordinates. This is the most common and easiest hand computation method when cross-section notes and/or plots are available. A variation of this method is called the double meridian distance (DMD) method. The cut (or fill) section is treated as a closed traverse, and the area is computed using the offsets (departures) and the depths (latitudes). Offset and depth at the slope-grade intersect (slope stake point) must be interpolated or scaled on the cross-section plot since these values are not measured in

the field. Likewise, a depth must be scaled at each channel toe. Automating this method requires the same interpolations at the toes and slope stake points. A cross-multiplication system is the simplest method of computing the (double) area of the section. As the density of points along a given cross section increases, this manual computation process can become time-consuming. When automated, the greater density approaches a truer representation of the bottom. An example of this computation is shown in Figure 15-4. In this example, pre- and post-dredge end areas are computed separately and relative to the (-) 40.0 foot payment prism. These end areas are combined for use in the AEA volume computation with adjacent cross-sectional areas. Alternatively, the payment end area (4,225 sq ft) could have been directly computed. It is usually desirable to compute available pay quantities as soon as the pre-dredge survey is completed (to compare with the bid quantity estimates); thus, the (usually) small amount of material remaining on the after-dredge survey is easily computed and deducted from the pre-dredge quantity.

(3) Planimeter (mechanical). A polar planimeter was once commonly used by many districts to measure areas directly from the section drawings. Although not as precise as a direct computation, it is typically accurate to about 1 or 2 percent of the computed end area. Normally, the end area was planimetered two or three times and the average taken as the final end area. The disadvantage is that large-scale sectional plots of the survey data and payment templates are required. Section drawings were retained with bid, pre-dredge, and post-dredge cross-sections plotted, the pay area in the cross-section in Figure 15-4 would be planimetered.

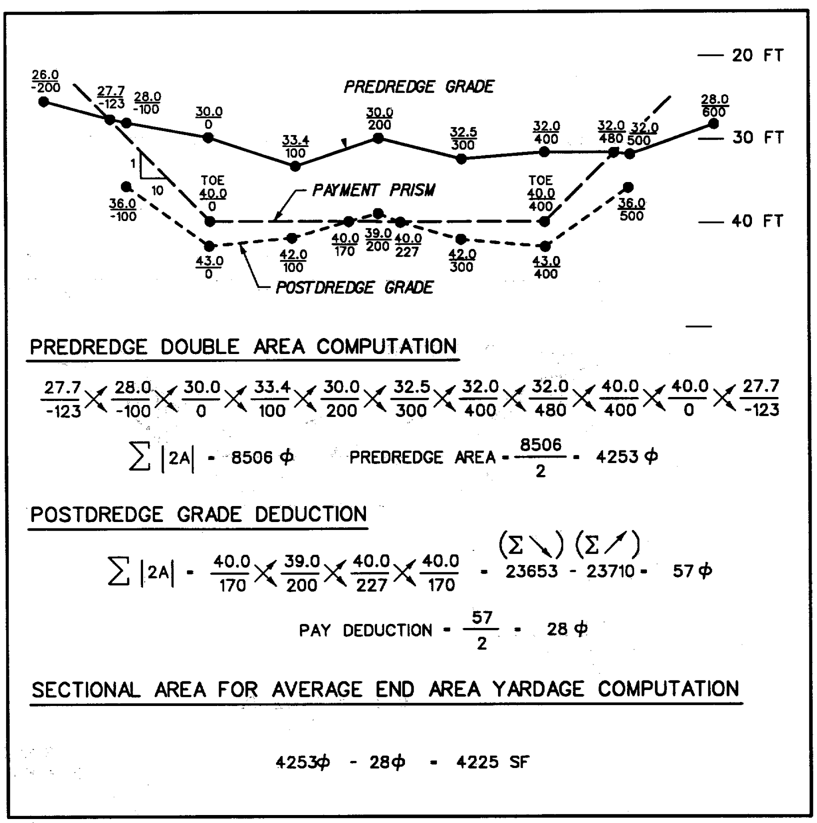


Figure 15-4. Typical predredge and postdredge quantity take-off by coordinate method

(4) Planimeter (digitizer). Sectional grades may be digitized on a tablet for direct computer area computation (Figure 15-5). An analog echo sounder tape can be directly digitized. More commonly, a final section drawing is used containing both the predredge and postdredge surveys. Occasionally, prebid surveys and intermediate partial payment surveys are plotted in section on this sheet for comparative purposes. In all cases, pay template data must be plotted in section for input as part of the area computation.

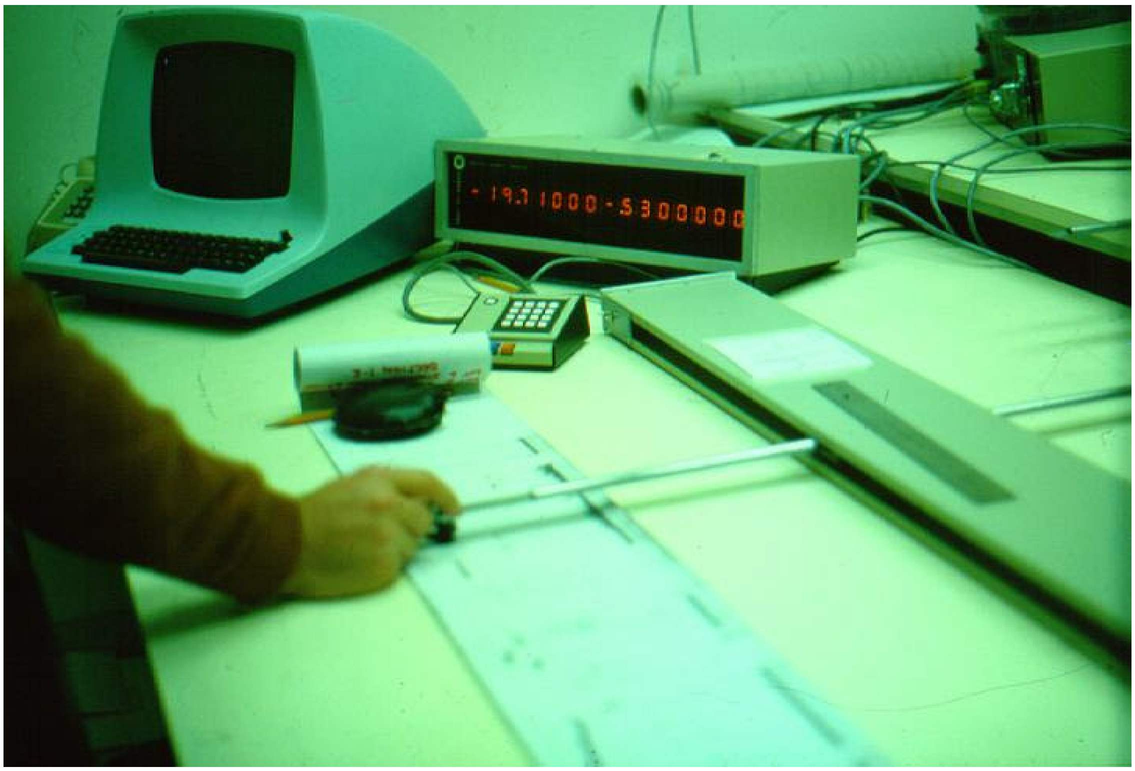


Figure 15-5. Automated quantity take-offs from digitizing tablet (ca 1976 Jacksonville District)

(5) Automated methods (numerical integration). Quantities may be directly computed on any automated computing device from digitized and/or field-automated hydrographic survey data. No sectional plot is necessary. The end area may be computed by a number of methods, such as coordinate/ DMD areas, summing trapezoidal elements, or numerical integration--see Figure 15-6. The first two methods require interpolation routines to determine toes and slope stake points, but the third method (numerical integration) does not. Numerical integration simply breaks up the cross-section at a fixed interval (e.g., 0.1 or 1 foot) and interpolates depths within this interval; summing up the small area increments across the channel to obtain the total sectional area. Most automated computation systems use this method to compute end areas--e.g., HYPACK MAX. In addition, upslope box cut payment allowances can be simply and directly computed using numerical integration methods.

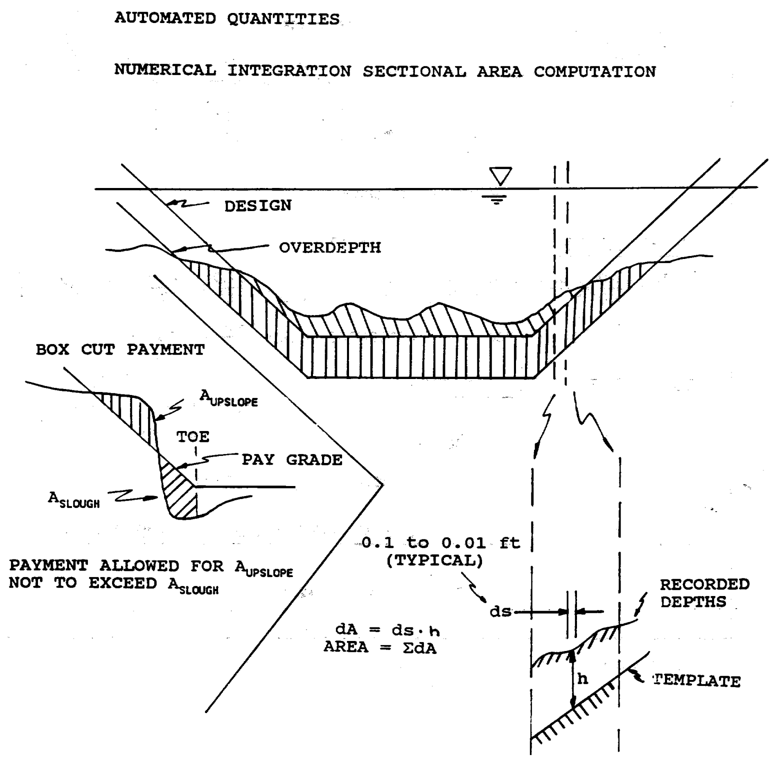


Figure 15-6. Automated quantity take-offs using numerical integration methods

15-4. Triangulation-Based Volume Computations (Triangulated Irregular Networks)

The Triangulated Irregular Network (TIN) volume technique is based on comparison of two terrain models. In the case of dredged material volumes, one model represents the actual bottom terrain as surveyed, and the other model usually represents a design surface (e.g., required depth, overdepth), although two surveyed surfaces can also be compared. TIN routines offer great flexibility in the collection of survey data, since the terrain coordinates need not be in any particular pattern or alignment. TIN programs also enable visual terrain models of the surveyed topography and of design, or hypothetical, terrain surfaces--see Figure 15-7. The TIN model volume is also more accurate than an AEA volume computed from the same data base. TIN routines for volume determination and terrain visualization are commonly available in commercial site design and some survey software packages. For dredged material volume applications, TIN routines are particularly well-suited to cases in which the channel is not a simple straight layout, such as in turning basins, settling basins, widener sections, curved channels, etc.

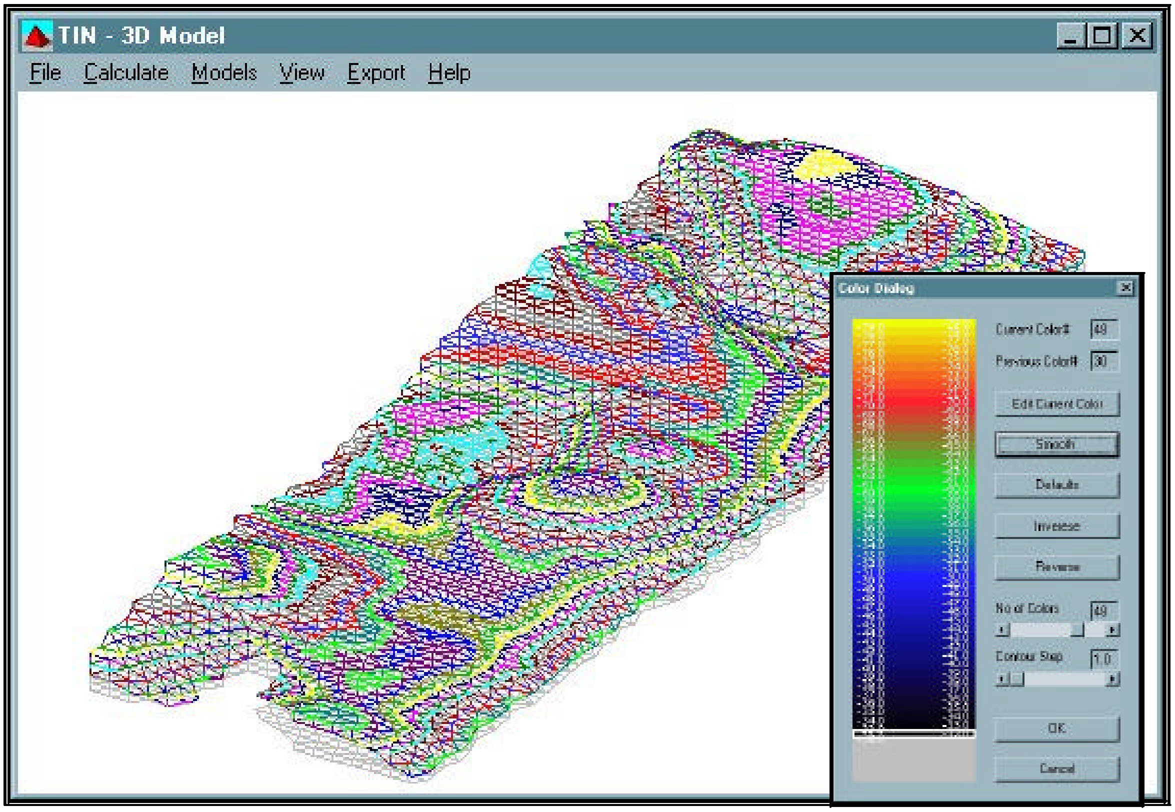


Figure 15-7. Color-coded three-dimensional TIN surface model (Coastal Oceanographics, Inc)

a. *General concept of TINs*. A TIN is actually a set of triangles which represents the terrain surface. Consider a set of survey coordinates marked on a map. These coordinates are "triangulated": a set of triangles is specified such that their vertices are these spatial points, no triangle contains coordinates other than its vertices, and the triangles cover the area of interest exactly and without overlapping each other. Any such set of triangles defines a TIN. The maximum area a TIN can cover is the "convex hull" of all coordinates. That convex hull is the polygon which contains all coordinates, whose vertices are the coordinates, and which is convex; that is, any straight line segment connecting two points in the interior of the polygon is entirely contained by the polygon. The convex hull of all coordinates is also the convex polygon of smallest area containing all coordinates. A TIN may fail to cover its maximum area while still covering all available coordinates; some triangles along the boundary may be missing.

b. Delaunay Principle for generating TINs. Any particular set of survey coordinates may be triangulated in many different ways, each yielding a different TIN. The Delaunay Principle, which is common in many TIN routines, is preferred for dredged material volumes. This procedure computes a unique TIN for a given set of coordinates and helps avoid long narrow triangles where possible. The Delaunay Principle requires that the circle circumscribed around any triangle in the TIN contain no points (soundings) in its interior. An exception to the uniqueness of the Delaunay TIN described above occurs when a circle circumscribed around a triangle in a Delaunay TIN contains on its circumference, but not in its interior, one or more sites in addition to the three triangle vertices. Such a case is called "degeneracy." In the presence of degeneracy, the Delaunay Principle fails to characterize a TIN uniquely for a given set of sites. Indeed, four sites on a circle can be triangulated in two different ways in accordance with the

Delaunay Principle. In the absence of degeneracies, however, the TIN constructed in accordance with the Delaunay Principle is unique. It is frequently assumed that the Delaunay TIN covers the maximum area, namely, the convex hull of all coordinates. As stated earlier, a TIN need not cover the maximum area--in fact, any triangulation process, aiming to fully cover the convex hull of a given set of points, tends to generate boundary triangles that are long and narrow, and may adversely affect displays and perhaps even some calculations. Typically, such triangles can be removed from the TIN while keeping all points covered and reducing the total area of the TIN by only a negligible amount. It is recommended, however, that software packages for TIN generation allow the user control over which boundary triangles to remove or at least document their rules for deleting triangles, if such rules are built into the software. Software packages such as HYPACK MAX allow for such input options when generating TINs

c. Terrain and design surfaces. The salient feature of the TIN volume methods is that they construct two surfaces, a TIN "terrain surface" developed from depth (elevation) measurements and a "design surface" which represents the design specifications. Terrain information consists typically of a list of X-Y-Z coordinates, with the horizontal coordinates specified by X-Y and the spatial coordinate z recording the measured elevation. When a TIN is generated for the given measurement sites (x_i,y_i) and the corresponding triangles and vertices (x_i,y_i,z_i) are joined in space, a terrain surface results. The design surface consists of polygonal surfaces. A desired design surface (navigation channel), for instance, is sometimes specified as a long rectangle with adjacent polygons for side slopes. X-Y points on the channel are termed "nodes." Polygonal surfaces are represented by their constituent planar polygons or "facets" in space. For input purposes, they are mainly defined in terms of "design breaklines," the line segments at which facets are joined. Those breaklines terminate at "design breakpoints." Typically three breaklines meet in a breakpoint.

d. Polygonal surfaces. TIN surfaces are also instances of polygonal surfaces. They represent the special case in which all polygonal facets are triangles. Polygonal surfaces are often represented, somewhat artificially, as a TIN surface if the polygonal facets are partitioned into triangles. In that case, breaklines are generic to all such surfaces. The design surfaces encountered in road construction, as well as in hydrographic applications, tend to be of a special form: their cross sections perpendicular to a center line are similar to each other. Some commercial packages, therefore, offer an alternate surface specification method suited to surfaces of this particular kind. The idea is to "push a template," that is, to interpolate a design surface through a sequence of cross-sectional design delineations or "templates." This design specification method is ideal for long stretches of channels. However, if a channel changes direction, side slopes vary, or more complex designs such as turning basins are used, the template method characterizes the true design surface only approximately.

e. Cut volume. The space bounded by the terrain and design surfaces defines the volume to be determined. This space is subdivided into vertical triangular prisms, that is, polytopes with three vertical edges capped by two, not necessarily parallel, triangles, as shown back in Figure 15-1. The volume of such a prism is rendered exactly by the formula

$$V = [(h_1 + h_2 + h_3)/3] \cdot (A_0) \tag{Eq 15-4}$$

where

h = height of vertices above design (pay) prism
A_0 = triangular area of prismoidal element projected on design surface

Thus, h_1,h_2,h_3 represent the lengths of the three vertical edges of the prism, and A_0 denotes the area of the triangle that arises as a vertical projection or footprint of the prisms onto a horizontal plane. Indeed, A_0 is the area of the underlying TIN triangle. The volumes of all the prisms that constitute the cut body are then added to arrive at its total volume. The cut volume is therefore calculated on a triangle-by-triangle basis. This requires, however, that the dredge area (that is, the projection of the cut body onto the reference plane) be fully triangulated.

(1) Note that some TIN triangles of the dredge area may be clipped by the boundary of the dredge area so that their remainders within the dredge area are non-triangular polygons, typically quadrangles. A straightforward way of dealing with this situation is to subdivide these polygons into triangles. In this fashion, the volume of the cut body, as defined by the TIN terrain surface, is rendered exactly. There are, in general, several different ways to subdivide a non-triangular polygon into triangles. Since each of the polygons to be subdivided is part of a TIN triangle corresponding to a planar region on the terrain.

(2) As with the average-end-area computation discussed previously, the user should be cautious of areas in which the design surface extends, in the x-y plane, beyond the terrain surface. In such areas, there exists no terrain surface with which to compare for volume information. Similarly, no volumes can be obtained for areas in which the terrain model has no corresponding design surface. TIN routines usually assume vertical bounds at the edges of the terrain and design surfaces. Therefore, volumes are only determined for those X-Y areas in which terrain and design information exists. Note that if vertical bounds are not created by the TIN routine, the program may produce erroneous results in those areas of discrepancy. The user should check the TIN routine for proper handling of terrain/design surface gaps.

f. Automated dredge volumes from TIN models. The TIN MODEL Program in HYPACK MAX is capable of calculating the volumes between two different surfaces. Three different options are currently available:

(1) Survey Surface vs. Level. This option compares a TIN surface against a level plane. This would be applicable to disposal or borrow area surveys. See example at Figure 15-8.

(2) Survey Surface vs. Channel. This is the most common dredging application--comparing a TIN surface against a standard channel prism that may contain irregular boundaries and side slopes. This would be the most common application for Corps navigation projects.

(3) Survey Surface vs. Second Survey Surface. This compares two TINs irrespective of any payment prism.

Details for automated volume computations using TIN models are found in the software manuals specific to the automated hydrographic data acquisition and processing system being used. Not all data acquisition software packages provide options for TIN volume computations relative to Corps navigation projects. Many programs regenerate cross-sections from a TIN model and compute quantities using AEA methods--an unnecessary and complex process if the design surface can be clearly defined.

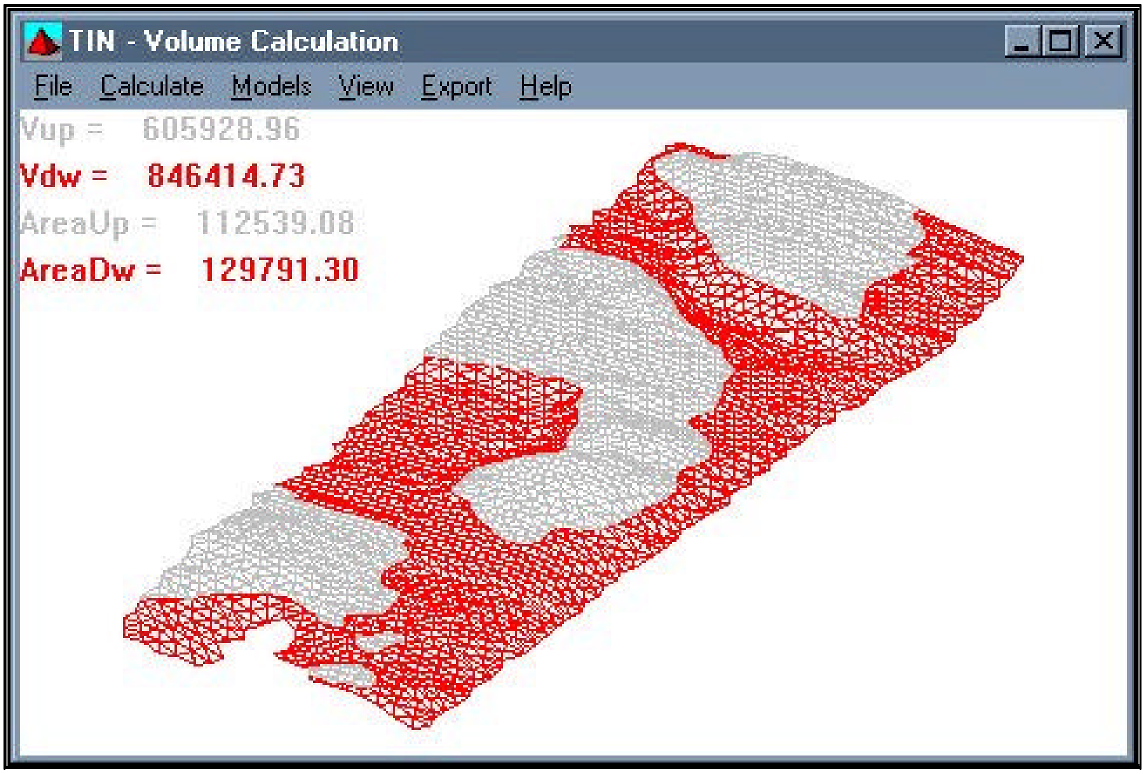


Figure 15-8. Example of TIN volume computed between TIN surface model and a level reference plane (Coastal Oceanographics, Inc.)

15-5. Reference Surfaces and Payment Templates used in Corps

There is no commonality among Corps districts in dredge payment methods or templates. Even Area Offices within districts are known to have unique payment methods. There at least a dozen distinct dredge payment methods used by Corps districts--e.g., Jacksonville Method, Grand Haven Method, Philadelphia Method, and Savannah Method. This variation adds complexity to attempts to standardize quantity computation software and impacts dredging firms working in different commands. Figure 15-9 depicts some, but not all, of the variations in dredge payment methods found in the Corps. This section describes some of the current variations is these payment methods.

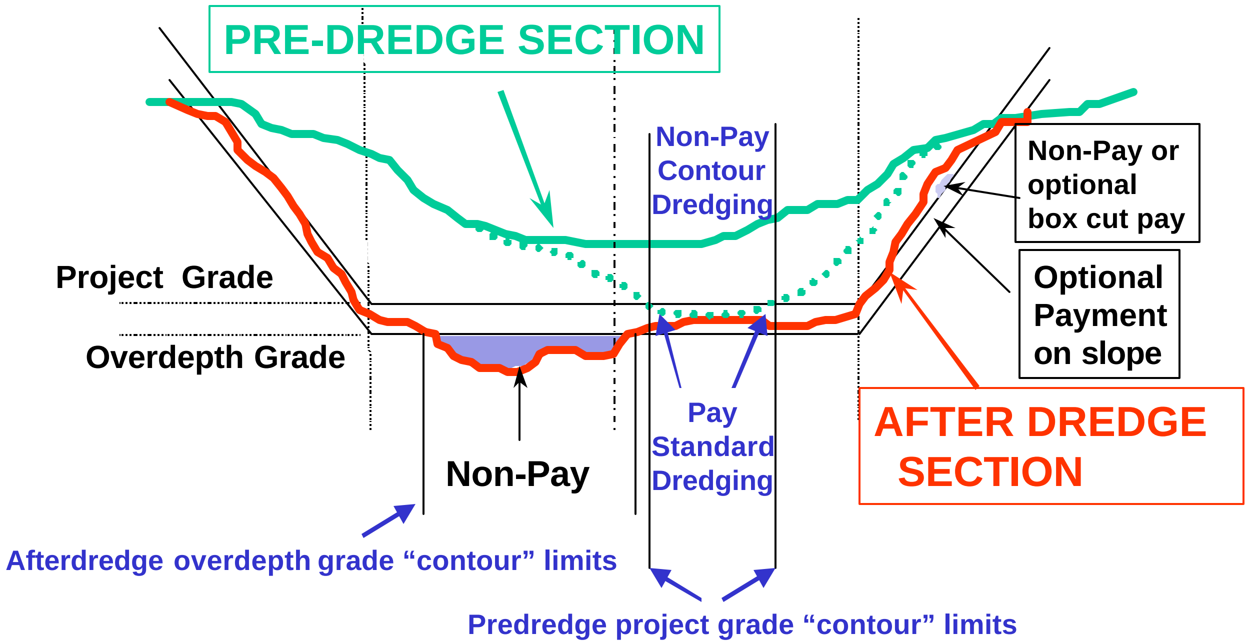


Figure 15-9. Various in-place dredge payment grades and templates used in Corps

a. Standard and Contour Dredging payment templates. In general, there are two somewhat common payment methods between the channel toes--the Standard Payment Method (Figure 15-10) and the Contour Dredging Payment Method (Figure 15-11). The major difference between the two methods is how material between the project grade and overdepth payment grade is handled. As shown in Figure 15-9, neither method pays for material excavated below the overdepth grade--the vertically shaded area lying to the left of the centerline. Both methods would pay for material excavated below the design grade (down to the overdepth grade) *provided the* Predredge (or P&S) survey indicated material existed above the design grade. If the predredge survey indicated the area was clear to the design grade (i.e., the dashed Predredge line in Figure 15-9), then the Contour Dredging Method would *not* allow payment for material excavated below the project grade. The Standard method would provide payment allowance for material removed in this area. Thus for the Contour Method, dredging payment limits are defined by the project grade depth contour for the predredge survey; the dredging pay limit for the Standard Method is defined by the overdepth grade contour for the afterdredge survey. Some districts using the Standard Method will place physical dredging limits within the channel for areas below project grade. This is, in effect, another form of Contour Dredging except the rigid dredging limits are used instead of the Predredge contours. This is illustrated in Figure 15-10 .

b. Side slope payment. Districts vary widely on payment for excavation in side slopes. Some districts treat side slopes the same as the main channel, and pay relative to the Standard Method or Contour Method. Others do not allow payment for any material removed from the side slopes (presumably such removal is factored into the unit price in the main channel). Some districts provide side slope excavation payment only on new work, not on maintenance dredging projects. Other districts provide for a box cut payment allowance, as was previously described and illustrated in Figure 15-3.

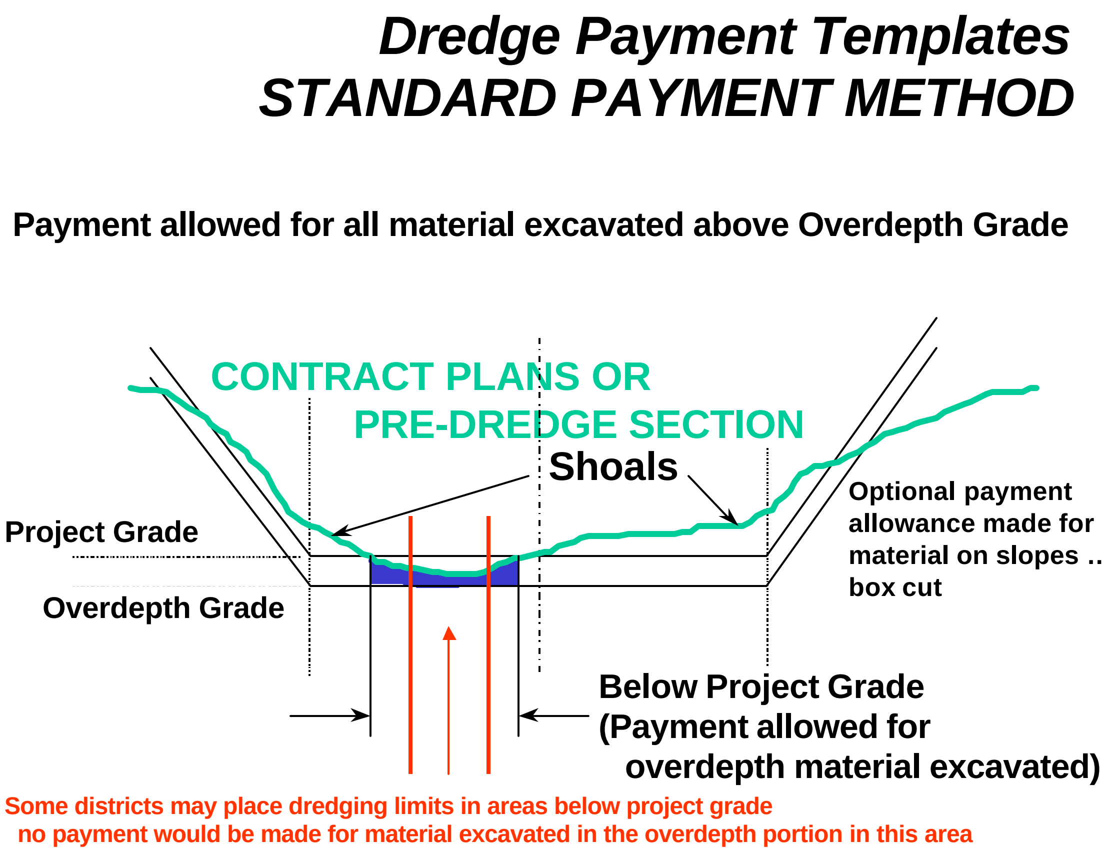


Figure 15-10. Standard Payment Method of computing excavated quantities

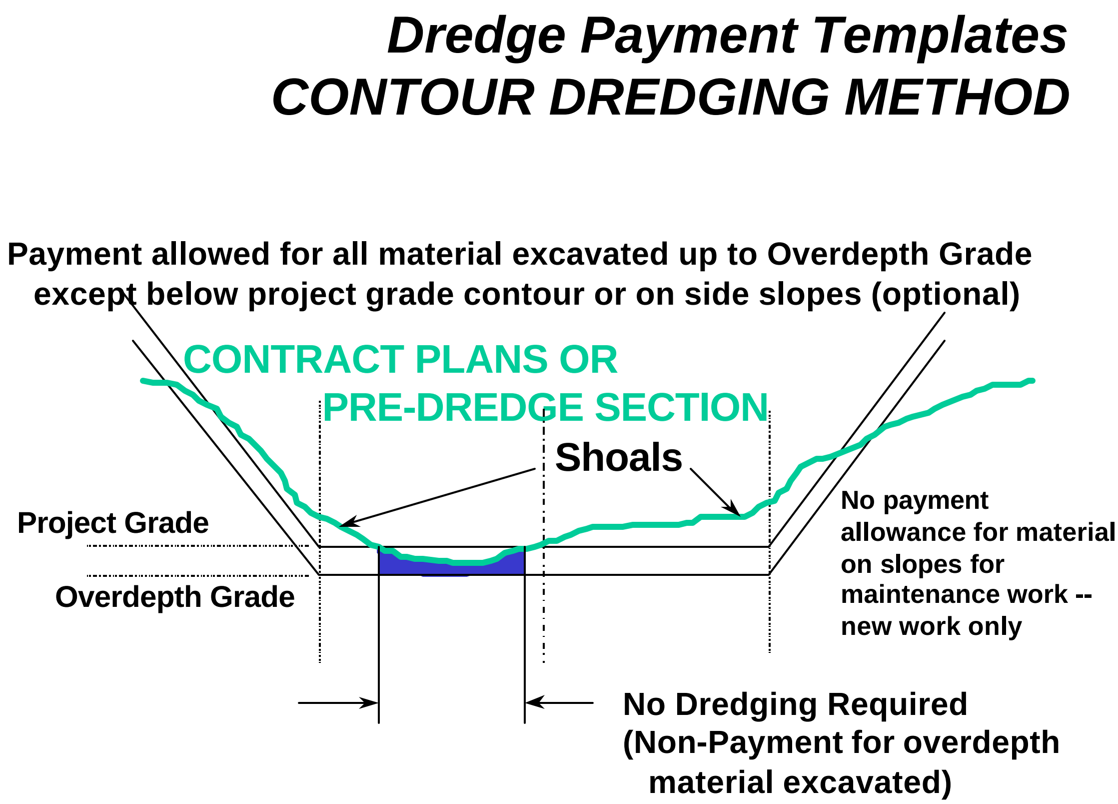
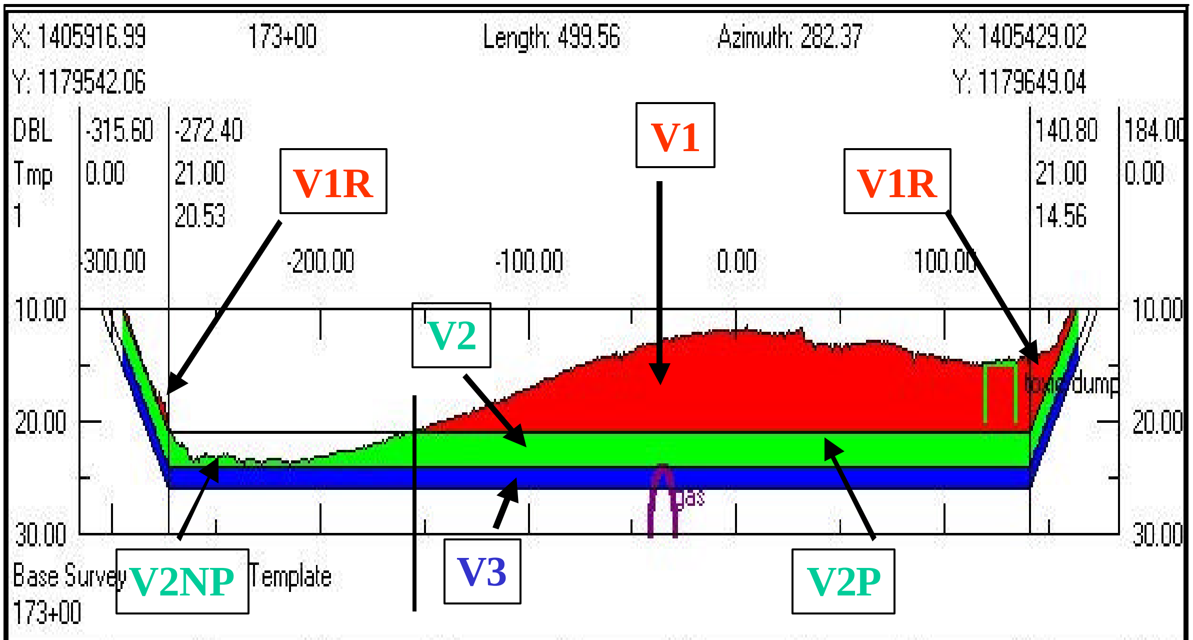


Figure 15-11. Contour Dredging Payment Method of computing excavated quantities

c. Automated software for computing dredged quantities. A number of software packages are available to compute AEA , TIN, or Binned volumes. Not all are designed to support the varied Corps dredging templates outlined above. Coastal Oceanographic's HYPACK MAX "Cross-Sections and Volumes" module is tailored to these varied payment templates; providing methods to determine both Standard and Contour Dredging payment computations, side slope restrictions, box cut allowances. This is illustrated in the cross-section in Figure 15-12. This example contains both the project grade ("design" grade) and overdepth grade ("subgrade") areas/volumes. It also adds a third template--termed a "supergrade"--which could be an advance maintenance grade limit or used for estimating quantities at different grades. Figure 15-12 also shows some of the subdivisions used by HYPACK to cover the various payment methods used in the Corps. These subdivided areas in the cross-section allow for separating Standard/Contour methods, side slope payment variations, and box cut allowances. All the subdivisions used in HYPACK MAX end area pay computations are listed below:

V1:	The volume of material above the design surface in the center of the channel.
V1L:	The volume of material above the design surface of the left bank.
V1R:	The volume of material above the design surface of the right bank.
V2:	The volume of material between the design and the overdepth grade surfaces in the channel center.
V2P:	The volume of material between the design and the overdepth grade surfaces in the channel center where the depth is less than the design surface.
V2NP:	The volume of material between the design and the overdepth grade surfaces in the channel center where the depth is greater than the design surface.
V2L:	The volume of material between the design and the overdepth grade surfaces of the left bank.
V2R:	The volume of material between the design and the overdepth grade surfaces of the right bank.
V3:	The volume of material between the overdepth grade and the supergrade surfaces in the channel center where the depth is less than the design surface.
V3L:	The volume of material between the overdepth grade and the supergrade surfaces of the left bank.
V3R:	The volume of material between the overdepth grade and the supergrade surfaces of the right bank.
X2:	The amount of material removed beneath the design surface by a box cut inside the channel toes. You may enter the distance used to consider box cuts.
X1:	The amount of material on the left or right banks that is above the design surface. X1 can be credited to fall into an X2 hole.
Y1:	The amount of material which has been deposited during the dredging process.

As an example of how the above zones are used to accommodate the differing payment methods, the V2 sector represents all material in the overdepth zone (between the toes); all of which would be paid under the Standard Method but only a portion of which is paid under the Contour Method. That portion is defined by the sectors V2P (Pay) and V2NP (Non-pay). The Contour Method would provide payment for the V2P sector, but the V2NP sector would not be paid since there was no material lying above the required depth. Contour Dredging Method volume computations require comparisons between the pre- and post-dredge surveys since payment is restricted to areas where material lies above the required grade on the pre-dredge survey. If material in the sector V2NP is excavated during dredging, it is not paid. The Contour Method presumes a degree of dredging accuracy that may not be achievable--especially in hopper dredging. Its intent is to avoid paying for substantial quantities of material lying below the required grade but above the overdepth grade. This material is paid in the Standard Method unless physical dredging limits are placed in areas where material lies below the required grade but above the overdepth grade.



	V1L	V2L	V3L	V1	V2	V3	V1R	V2R	V3R
M^2 Area	10.92	66.37	44.30	1887.69	1034.40	826.40	66.12	70.47	46.98
M^3 Vol	2079.63	3871.96	2583.12	154728.36	87948.91	71781.08	8149.11	6769.14	4512.76
Accum	18026.32	25509.85	24360.63	432641.20	375088.80	291356.21	40325.35	26073.35	17594.94

Figure 15-12. Channel cross-section with areas/volumes for various portions of excavation areas Not all subdivisions shown (Coastal Oceanographics, Inc End Area Method)

The following sample computation is performed over a 1,188 ft dredging acceptance section. The output is from Coastal Oceanographics' HYPACK program and uses the "Philadelphia Method" option for volume computations. The channel limits are irregular as shown by varying offsets for each cross-section—this dredging section encompasses a channel widener. The final yardage values represent the material available on the pre-dredge survey. A similar take off would be made on the after-dredge survey and any remaining material from that survey would be subtracted from the pre-dredge results.

Tampa Harbor, Cut-D (HB), Acceptance Section - 3
Office Engineering Section, Survey Branch, Jacksonville District
Pre-Dredge Survey (No. 98-C041) Cont. No. DACW17-98-C-0004
Date of Survey: 24 February 1998

Station to Station		Project Depth	Over Depth	Left Slope	Right Slope
61+00	72+88	34.0	36.0	3.0/1	3.0/1

Dredging Quantities Summary
==========================

Total Material to Project Depth	11309.4 CY
Total Allowable Overdepth	11853.4 CY
Total Pay Place	23162.8 CY

Dredging Quantities Computation
==============================

	-------- Reference Depth = 34.0 ft -------					------------ Overdepth = 2 ft ------------				
Station	Left Slope	Left Channel	Right Channel	Right Slope	Volume (CY)	Left Slope	Left Channel	Right Channel	Right Slope	Volume (CY)
61+00	0.0	0.3	0.0	0.0	0	2.0	4.0	0.0	0.0	0
Offset:	-302	-200	+200	+302						
62+00	11.6	99.2	50.3	5.9	309.8	20.0	134.0	98.0	12.0	500.1
Offset:	-302	-200	+200	+302						
63+00	24.5	172.3	33.5	5.6	746.2	26.0	144.0	98.0	14.0	1011.2
Offset:	-302	-200	+200	+302						
64+00	24.4	204.4	26.6	4.6	918.7	26.0	158.0	72.0	12.0	1018.6
Offset:	-302	-200	+200	+302						
65+00	33.5	191.5	0.5	0.1	900.2	28.0	166.0	8.0	2.0	876.2
Offset:	-302	-200	+210	+317						
66+00	29.3	188.5	7.9	1.5	837.9	26.0	170.0	34.0	6.0	812.9
Offset:	-302	-200	+239	+346						
67+00	27.5	194.2	24.7	12.0	931.3	30.0	174.0	50.0	22.0	969.3
Offset:	-303	-200	+262	+367						
68+00	37.8	261.4	10.3	2.1	1093.6	34.0	202.0	32.0	8.0	1045.7
Offset:	-303	-201	+290	+394						
69+00	38.2	277.7	0.0	0.0	1210.2	34.0	200.0	0.0	0.0	978.6
Offset:	-305	-201	+314	+418						
70+00	33.9	239.1	5.4	1.1	1143.2	32.0	200.0	24.0	6.0	946.2
Offset:	-306	-203	+341	+444						
71+00	29.2	214.7	53.5	5.7	1095.9	30.0	190.0	132.0	12.0	1150.8
Offset:	-309	-204	+369	+469						
72+00	22.8	201.6	84.4	13.5	1145.0	24.0	202.0	142.0	20.0	1349.4
Offset:	-312	-206	+395	+497						
72+88	10.0	176.8	96.9	14.3	977.4	16.0	218.0	124.0	18.0	1194.5
Offset:	-315	-208	+419	+521						

15-6. Volumes of Irregular Channels or Basins

Average End Area computation methods become complex when channel sections have varying limits, at channel intersections with widener sections present, in irregularly shaped turning basins, or when survey cross-sections are not run perpendicular to the channel alignment. When cross sections are not run normal, or perpendicular, to the project centerline, the section's projected intercept with the side slope must be adjusted in section plots or automated software when computing end areas. This commonly occurs in turning basins and widener sections. The plotted side slope is corrected as a function of the sine of the angle of intercept (e.g., if a survey line intersects a 3-on-1 slope at 75 deg, the plot of the intersection would be shown as 3.1 to 1). Average-end-area projections are made relative to the actual survey spacing interval, not to the project alignment stationing. In areas where different sectional alignments merge, irregularly shaped triangular or trapezoidal surface areas result. Various methods are employed to proportionately distribute end areas over these irregular areas (see Figure 15-13).

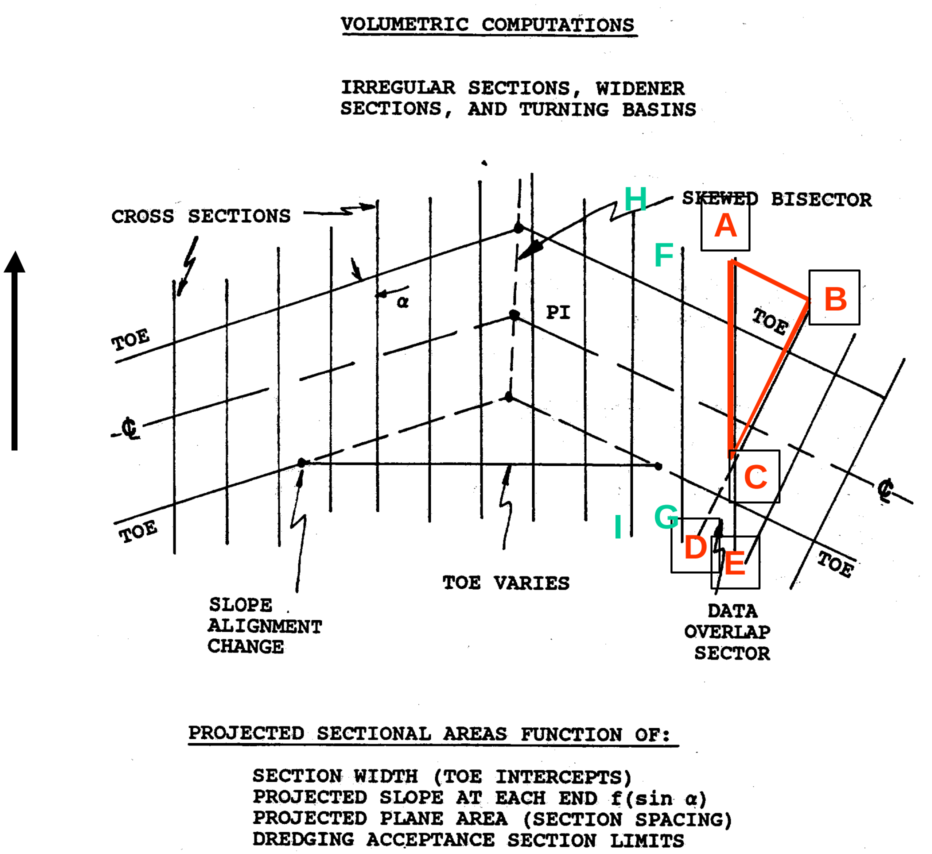


Figure 15-13. Volumes of irregular channels and non-normal cross-section alignments

a. In Figure 15-13, volumes for each of the irregular sections must be computed. An example is the triangular area (A-B-C) where the cross-sections from two different alignments overlap. The end area for the cross-section B-D is not projected to the left of the section. It is broken up into end areas B-C and C-D which are projected to varying distances depending on the surface area of the irregular figures between sections--i.e., triangles A-B-C and C-D-E.

b. The volume within triangle A-B-C illustrates the complexity in determining average end area quantities for irregular areas. Since the cross-sections are not on the same alignment, the distance to project the "average" of their end areas is difficult to determine--it can only be approximated. In addition, section A-C intersects the side slope at an angle, requiring a correction for the end area of the upslope portion of the section. It is often simpler to treat the area A-B-C as a vertical prismoidal element, computing the volume of the prism using averages of depths along the sides. The triangle could be further broken to separate out the channel portion from the side slope. Likewise the volume of the element C-D-E could be similarly computed. This element would be deducted from volumes computed from the cross-sections A-E and F-G.

c. Volumes beginning with cross-section F-G may be computed from average end area projected along the original cross-sectional spacing (e.g., 100 ft). The end areas for each section need to be corrected for the non-normal slope intersect. This may require plotting and viewing cross-sections in profile. In addition, once the widener section is reached at section H-I, both toe ranges begin to vary and must be computed. The slope on the widener is normal but skewed on the north side of the channel.

d. The above example clearly illustrates the difficulty in using average end area techniques for irregular shapes or non-normal sections. Quantity estimates in such areas are truly "estimates" and are often educated guesses. For this reason, TIN or Bin volume computation techniques should be employed. The irregular channel template surface (nodes and slopes) can be input as a terrain model, as shown in Figure 15-14. The surface model (TIN or bin) is then not dependent on the survey alignment method. The volume is simply computed between the two surfaces as explained earlier. HYPACK MAX contains an optional volume program ("Standard HYPACK") that is designed to compute quantities in irregular basins or where survey lines are non-parallel. "Standard HYPACK" slices horizontal wedges between cross-sections--similar to TIN elements--as illustrated in Figure 15-14.

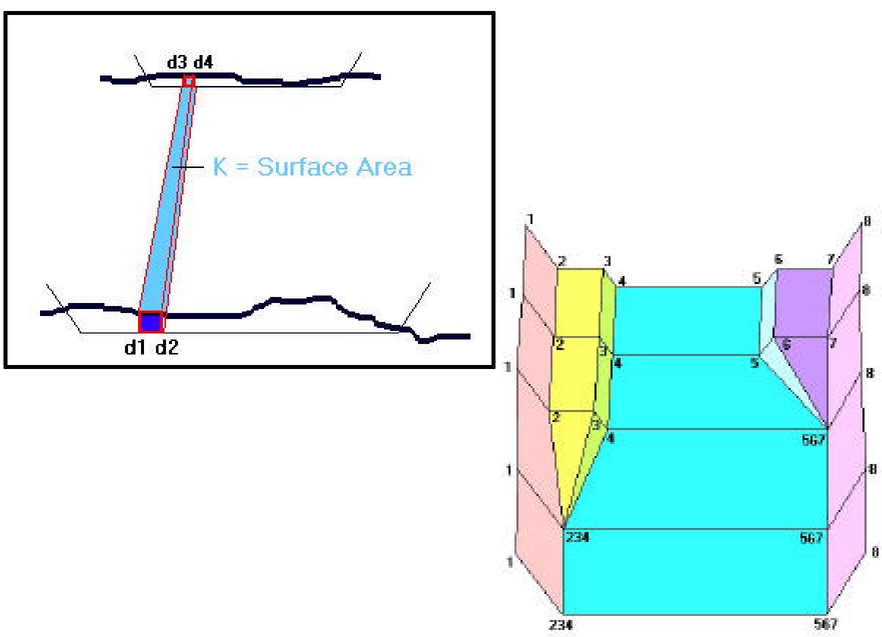


Figure 15-14. Standard HYPACK method for computing quantities in irregular sections. This method is designed for irregular basins and/or non-parallel cross-sections

e. Curved channel sections. Some Corps navigation projects are defined relative to a circular alignment and cross-sections are taken normal to that alignment. These sections may be in the navigation or flood control project or up the overbank levees. In the case of curved alignments with cross sections run perpendicular to the alignment, average end areas are projected about the radius of the centroid for each section in order to compute the volume. Various mechanical and numerical methods exist for computing the centroids of irregular areas (see Figure 15-15).

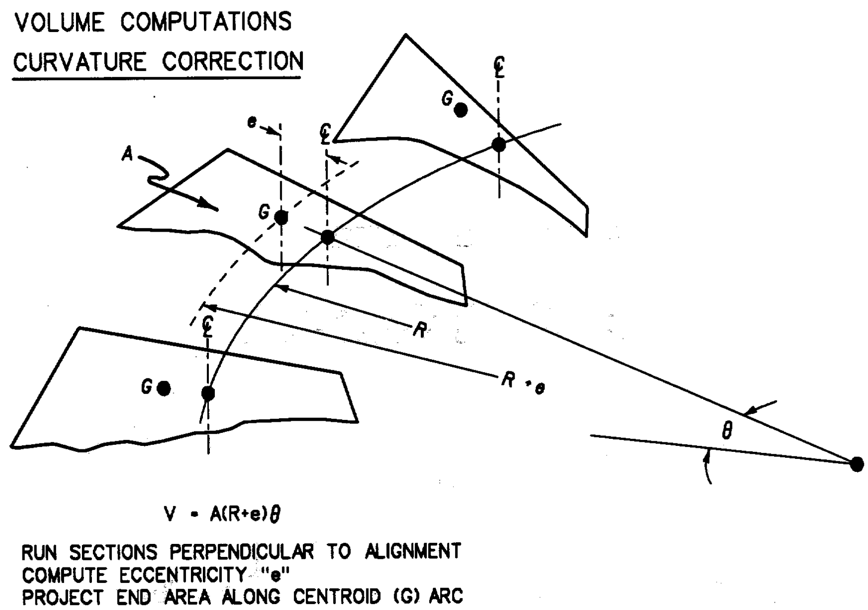


Figure 15-15. Curved channel volume computations

15-7. Obtaining Complete Coverage for Quantity Computations

A major survey deficiency exists when complete coverage is not obtained over the entire payment area. This often occurs when deep-draft survey vessels are unable to survey into shallow waters where excavation was performed. In other cases, the slope-grade intersect point may be above the surface, requiring land topographic survey coverage at the junction area. In either case, volume computations are impossible without full coverage through the slope-grade intersect points. This is the case regardless of the computation method (AEA or TIN). The distance that coverage is required outside the toe of a channel may be estimated by the following:

$$d = Slope \cdot (Required\ depth - Upslope\ depth) \qquad \text{(Eq 15-5)}$$

where:

	d	=	slope-grade intersect distance from toe
	Slope	=	design slope ratio (H/V)
	Required depth	=	project design or overdepth
	Upslope depth	=	average minimum depth atop slope/bank

It is essential that coverages be verified prior to computing quantities using automated software. Most programs have no alarm to indicate inadequate coverage. Verifying coverage is done by viewing 3-D models or section views of the project to ensure coverage.

15-8. Accuracy of Excavated Quantity Estimates

As described in detail in Chapter 4, the accuracy of a resultant volume is dependent on many random variables, each with its own accuracy estimates. These include horizontal positioning accuracy, elevation (or depth) measurement accuracy, data density or ensonified footprint size relative to the overall area, terrain uniformity, and the volume computational method employed. When average end area computations are made from widely-spaced cross-sections, three options are available to increase the accuracy of a given reach of channel:

- Decrease cross-section spacing
- Increase density and accuracy of data along the section
- Account for variations in cross-section spacing; do not assume spacing is constant on adjacent cross sections.

a. With single-transducer surveys, all of the above options have practical and economic limitations. Decreasing the cross-section spacing is easily achieved by use of multiple transducer or multibeam systems. This provides the greatest increase in accuracy. Increasing the density of data along a given cross-section will not improve the volume computations if the sections are spaced 200 feet apart. Likewise increasing the accuracy of data points in sections spaced 200 feet apart will not significantly improve the overall accuracy of the volume. No increase in section spacing will compensate for a constant 0.5-ft bias in depth. Likewise, the impact of a constant 20-ft horizontal bias on the side slopes cannot be compensated for in the volume algorithms. A large variance between two end areas can cause a significant error in yardage when the AEA formula is used.

b. In an effort to standardize average-end-area applications for single-transducer surveys, the following guidelines are specified:

(1) Care should be taken to reestablish the same section lines at each subsequent survey of the same area (i.e., predredge and postdredge surveys).

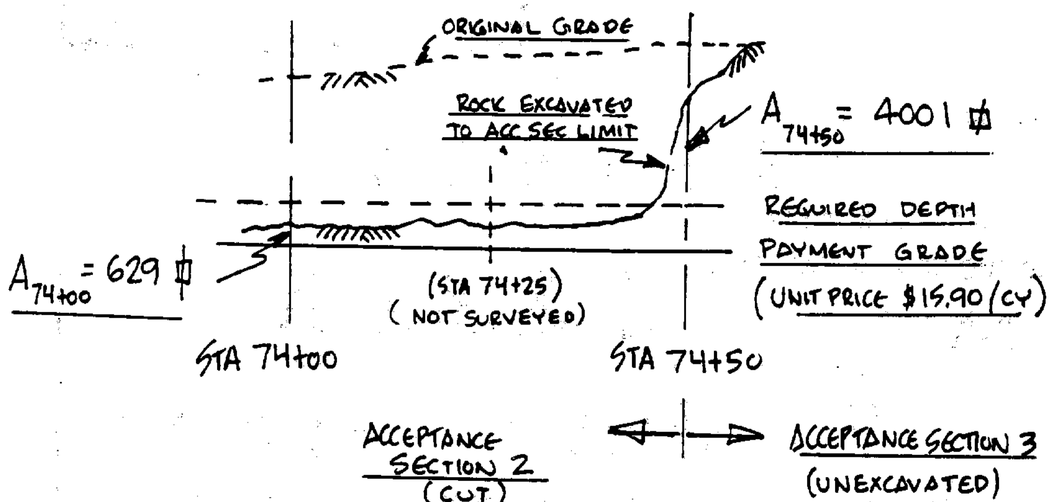
(2) Survey coverage should be slightly extended into undisturbed areas atop the slope, well clear of any excavation. When preconstruction and post-construction surveys are plotted and superimposed, these undisturbed regions should match in elevation. If not, a survey deficiency is indicated.

(3) Adhere to the survey coverage and line spacing specifications in Table 3-1. Standardizing cross-section spacing will help standardize volume computations. Obtaining full-bottom coverage provides the greatest benefit in increasing accuracy of volumes.

(4) The areal extent of all irregularities shall be fully determined. When a particular cross-section detects a bottom feature not considered typical of the entire space between adjoining sections, this feature should be densely covered with additional cross sections (e.g., 25 or 50 ft O/C; see Figures 15-16 and 15-17).

SUBJECT:	COMPUTED BY:	DATE:	FILE NO.
CROSS-SECTIONAL DENSITY	WA BERGEN	JAN 90	1110-2-1003
	CHECKED BY:	DATE:	SHEET NO.

(PROFILE)



AFTER DREDGE SECTIONS RUN 50 FT O/C

PAYMENT DEDUCTION FROM AVERAGE END AREA COMPUTATION

$$V_{AEA} = \frac{L}{27\,CF/CY}\,\frac{(A_{74+00} + A_{74+50})}{2} = \frac{50}{27}\left(\frac{629+4001}{2}\right) = \underline{\underline{4287\text{ CY}\quad(\$68,163)}}$$

PAYMENT DEDUCTION USING PRISMOIDAL COMPUTATION (ASSUME $A_{74+25} \approx A_{74+00}$)

$$V_{PRI} = \frac{L}{27\,CF/CY}\,\frac{(A_{74+00} + 4 \times A_{74+25} + A_{74+50})}{6} = \frac{50}{27}\left(\frac{629 + 4(629) + 4001}{6}\right)$$

$$V_{PRI} = \underline{\underline{2205\text{ CY}\quad(\$35,060)}}$$

[UNDERPAYMENT (TO CONTRACTOR) -- $33,103]

PRISMOIDAL COMPUTATION MORE CLOSELY APPROXIMATES ACTUAL EXCAVATED QUANTITY

Figure 15-16. Effect of inadequate cross-sectional density

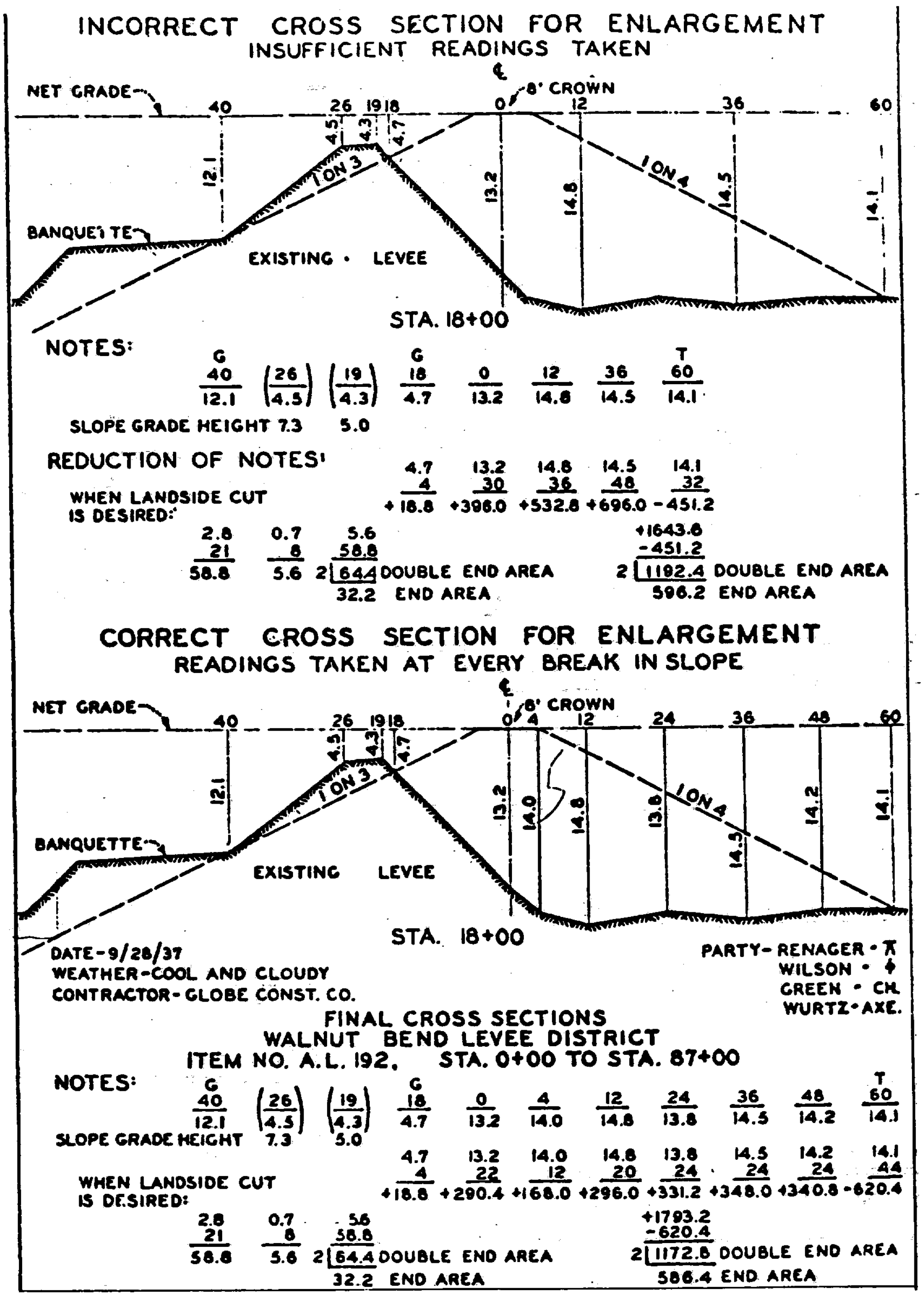


Figure 15-17. Effect of insufficient density along a levee cross-section

c. Accuracy and refinement of volume estimates. As with the average-end-area and any other volume computation technique, TIN volume estimates are improved with additional survey data. Conversely, the absence of data around bottom features could lead to large inaccuracies. For example, if no survey data is collected on a mound or shoal, the resulting computed volume would be an underestimate. Although there is clearly a benefit from more survey data, there is certainly a limit to the amount that can be collected from conventional single-beam sounding systems. However, an efficient means to obtain more survey coverage is the addition of longitudinal lines for cross-section surveys, or the addition of cross-section lines for longitudinal surveys. Unlike the average-end-area method, the TIN technique can process these combined data sets. Note also that the TIN technique offers a method of effectively processing data from multibeam survey systems for volume estimates. TIN routines commonly offer a method of refining the triangulated terrain model based on breaklines. Such line segments, entered by the user, prevent triangles from crossing these lines. This procedure might be used to break up large triangles or better model a feature, such as a ridge or channel toe. Although the addition of breaklines may not always be feasible or even possible, the use of additional terrain data will nevertheless only improve results.

15-9. Combined TIN and Average-End-Area Volume Computations

A variation of the TIN technique commonly available in site design packages involves a combination of TIN and average-end-area methodologies. This combination, which sometimes is simply labeled an average-end-area method, uses the flexibility of the TIN method in employing all survey data, yet permits the user to utilize average-end-area procedures.

a. Like the TIN technique, this combined method creates a TIN terrain model from the survey coordinates. Cross-sectional areas, as described earlier, are then extracted from the TIN at fixed intervals. These areas are bounded by a design template and the corresponding cross-sectional pass through the TIN. The end-area volume between two cross-sections is calculated by Eq 15-1.

b. This combined TIN/average-end-area method can be used on any dataset, including combined cross-sectional/longitudinal survey data. Cross sections can also be placed at arbitrary spacing and locations. However, if only cross-sectional survey data is used, note that no additional volume accuracy is gained if the spacing of the extracted cross-sections is closer than that of the original survey data cross-sections.

c. Since the volume results of the combined method are based on end-areas and not the full terrain model, this technique is generally less accurate than the TIN method. However, results in most cases will be more accurate than average-end-area, since cross sections are based on interpolated, and not projected, terrain data. The combined method also offers more flexibility in the collection of survey data.

d. This method also has application when full-coverage survey models are available and cross-sections need to be cut (generated) from the model--for profile viewing or other purposes. HYPACK MAX surface modeling (TIN) program has options to create regularly spaced cross-sections from TIN models, and to use these cross-sections for average end area computations if desired.

15-10. Example of Using TIN Methods to Compute Dredged Volumes (Baltimore District)

A dredging project on a tributary to the Potomac River was conducted by the Baltimore District using the TIN technique for dredged material volumes. This site featured a turning basin 200 ft long by 160 ft wide, and a channel 4,000 ft long by 60 ft wide leading to the Potomac River. The channel was dredged to 6 ft with an additional 2-ft overdepth. The survey data, derived from before- and after-dredge surveys, totaled 16,250 points and 15,112 points, respectively. The design surface was created using an interactive software package that allows a user to create basic channel designs with the input of only some basic parameters. Three software packages were used to calculate the dredged material volumes: Volest, a Fortran routine written by the National Institute of Standards and Technology (NIST), which runs on a UNIX workstation; Inroads, a civil/site UNIX software package written by Intergraph Corporation; and Roadworks, a civil/site PC software package written by AEC Group, Inc.

a. The volume results from a before-dredge survey for dredge depths of 6, 7, and 8 ft are seen in Table 15-1. The before-dredge data shows excellent correlation between all three software routines. There was no difference in results obtained from the INROADS and ROAD WORKS packages, and only minute differences with the Volest routine. As can be seen from Table 15-1, as the channel depth increases, the relative difference between the three routines decreases. If volumes for a deeper channel had been calculated, the relative differences between the routines would have become nonexistent. However, volumes for channel depths much greater than 8 ft could not be calculated because the side slopes of the channel would not intersect the narrow DTM created by the survey data.

b. *Further TIN analysis for dredge applications.* A characteristic of TINS that can cause concern is the occurrence of relatively large triangles. Large triangles can be caused when both cross-sectional and longitudinal lines of survey data are included in the triangulation. These triangles are most pronounced when there is only one longitudinal line through the cross sections. With more longitudinal lines added the big triangles are reduced in size and the corresponding volume calculation becomes more accurate. However, it has been shown that even with cross-sectional and a single line of longitudinal data (and resultant big triangles), the volume result is more accurate than that obtained with cross-sectional data alone. To illustrate this point, a test case was run using data obtained from Bonum Creek. Station 2575-2700 was used and the design surface was taken to be at a depth of 8 ft. The volume computed for station 2575-2700 using all the data at 8 ft was 1,781 cu yd. This can be considered a highly accurate volume because of the large amount of data collected and the resultant accurate TIN model. The average-end-area volume calculated was 1,618 cu yd, an underestimate of 9.2%.

Table 15-1
Change in Volume Computation with a Change in Channel Depth

		Navigation Channel Volumes (cubic feet)			
Depth of the Design Surface	Software Package	Between Stations 0-200	Between Stations 200-300	Between Stations 1827-3982	Total Volume
6 ft template	INROADS	845	81	10206	11132
	ROAD WORKS	845	81	10207	11133
	VOLEST	845	81	10198	11124
7 ft template	INROADS	2099	320	15542	17961
	ROAD WORKS	2099	320	15542	17961
	VOLEST	2099	320	15532	17951
8 ft template	INROADS	3414	582	21851	25847
	ROAD WORKS	3414	582	21851	25847
	VOLEST	3414	582	21845	25841

15-11. USACE Dredge Volume Computation Standards

Table 15-2. Dredge Payment Standards for Corps of Engineers Surveys

QUANTITY TAKE-OFF STANDARD	PROJECT CLASSIFICATION Navigation & Dredging Support Surveys Bottom Material Classification Hard	 Soft
CORPS-WIDE STANDARD PAYMENT TEMPLATE		
New work or Deepening	Standard Method	Standard Method
Maintenance dredging		
Hopper/hydraulic	Standard Method	Standard Method
Bucket/cutterhead	Contour Dredging Method	Contour Dredging Method
SIDE SLOPE EXCAVATION PAYMENT		
New work	Payment required	Payment required
Maintenance dredging	Payment required	Optional
BOX CUT PAYMENT ALLOWANCE		
New work	Optional	No allowance
Maintenance	Optional	No allowance
Limits of payment	25 ft inside toe	N/A
MAXIMUM BIN SIZE FOR GRIDDED DATA	1 m x 1 m	5 m x 5 m
DATA SET THINNING ALLOWED	No	Optional

VOLUME COMPUTATION METHOD	**Average End Area**	**TIN or Bin/Grid**
CROSS-SECTION DATA		
spaced > or = 100 ft C/C	No	recommended
spaced < 100 ft C/C	optional	preferred
MIXED CROSS-SECTIONS AND CROSS-LINES	No	recommended
MULTIPLE TRANSDUCER OR MULTIBEAM SWEEPS	No	recommended
IRREGULAR BASINS OR WIDENERS	No	recommended
SOFTWARE COMPUTATION VERIFICATION	Yes	Yes
Average end area accuracy	0.1 sf	0.1 sf
TIN accuracy	1 cy	1 cy

a. Corps standard payment template. Both the Contour and Standard payment templates may be used, depending on the dredging platform and purpose, as shown in Table 15-2. These two payment methods are depicted in the templates shown in Figures 15-10 and 15-11. Note that the Standard payment template shown in Figure 15-10 is used for hopper dredging.

b. Side slope payment. In general, payment should be made for material lying above either the overdepth or required grade on the side slopes. Side slope payment is optional on maintenance dredging in soft material. No payment might be made where there is minimal build up of shoal material along the toes, say less than 2 feet above required grade. If there is a major build up of material along the toe and extending into the side slope, then side slope payment would be warranted. Standard Methods should be used for computing side slope quantities.

c. Box cut allowance. A box cut payment may optionally be paid on hard material only. Pay allowance should be made in non-pay areas lying any distance outside the channel toe and up to 25 feet inside the toe. Payment is not restricted to any depth below project grade. Payment cannot exceed the amount of above-grade material capable of sloughing into the cut areas. Continued use of the box cut allowance is discouraged due to computational disparities in software packages, disputes over payment techniques, and usually insignificant yardage allowances for box cuts on actual projects.

d. Volume computation method. Average end area methods should be used only for closely spaced cross-sectional or gridded data. Otherwise, digital terrain model or TIN differencing methods are recommended. TIN methods should be used where cross-sections exceed 100 ft. TIN methods should also be used for mixed cross-section and cross-line data in order to utilize the full data set. Where full-bottom coverage is available, TIN or Bin volume techniques are recommended even though AEA methods using the full data set would yield approximately the same results. Terrain model differencing is recommended for irregular basins or channels. Construction contract specifications shall specify specific computation requirements.

e. Thinning and binning data sets. Thinning data sets is not recommended for dredge volume computations. There is no need to bin data sets if TIN volume computations are performed. Binning may be necessary if there are overlapping data sets. If multibeam data sets are binned, the bin size should be kept to a minimum--i.e., less that 1 meter or smaller. The shot point nearest the bin centroid should be used. If the terrain is smooth, then the bin size may be increased.

f. Volume computation software verification. Automated volume computation software shall be initially tested to ensure accurate, repeatable values are being computed. This is done by comparison with a manual computation. An average end area computation may be checked by using data points from a single cross-section and computing the section end-area by the exact coordinate method described in paragraph 15-3. At least 100 data points on the cross-section should be used. The manual and automated sectional end areas should agree to well within 0.1 sq ft. Both Standard and Contour Payment Templates shall be tested with data points located over all payment zones. Box cut computational accuracy should similarly be tested and verified, using data from simulated pre and post dredging surveys. The survey data should have multiple intersect points with the template. TIN volume computations may be tested by comparing volumes computed from densely spaced AEA sections passed through the TIN model--e.g., 1-ft cross-sections cut through a 100-ft section of the model. Volumes should agree within one cubic yard. Automated software should be reverified at each upgrade.

15-12. Mandatory Requirements

The standard requirements specified in paragraph 15-11 and Table 15-2 are mandatory.